4-1995

Using GIS to identify critical areas for water quality protection in New York City's water supply system

Paul K. Barten
Yale University

Krystyna Anne Stave
University of Nevada, Las Vegas, krystyna.stave@unlv.edu

PROCEEDINGS
AMERICAN WATER RESOURCES ASSOCIATION

Annual Spring Symposium

Water in the 21st Century: Conservation, Demand, and Supply

Edited by

LLOYD H. AUSTIN
Division of Water Resources
1636 West North Temple, Suite 310
Salt Lake City, Utah 84116

In Cooperation With

AWRA UTAH STATE SECTION
BRIGHAM YOUNG UNIVERSITY
UTAH STATE UNIVERSITY

Sponsors

CENTRAL UTAH WATER CONSERVANCY DISTRICT
METROPOLITAN WATER DISTRICT OF SALT LAKE CITY
UTAH DIVISION OF WATER RESOURCES
UTAH POWER AND LIGHT

Contributors

BALLARD, SPAHR, ANDREWS AND INGERSOLL
CH2M HILL
CLYDE, SNOW AND SWENSON
DAMES AND MOORE
ZIONS BANK PUBLIC FINANCE
ECKHOFF, WATSON AND PREATOR ENGINEERING
FRANSON-NOBLE AND ASSOCIATES, INC.
HANSEN, ALLEN AND LUCE, INC.
MONTGOMERY WATSON AMERICAS, INC.
PARSONS, BEHLE AND LATIMER

APRIL 23-26, 1995
SALT LAKE CITY, UTAH

AMERICAN WATER RESOURCES ASSOCIATION
950 HERNDON PARKWAY, SUITE 300
HERNDON, VA 22070-5528
(703) 904-1225/ FAX: (703) 904-1228

AWRA

WATER IN THE 21ST CENTURY: CONSERVATION, DEMAND, AND SUPPLY
AMERICAN WATER RESOURCES ASSOCIATION APRIL 1995

USING GIS TO IDENTIFY CRITICAL AREAS FOR WATER QUALITY PROTECTION IN NEW YORK CITY'S WATER SUPPLY SYSTEM

Paul K. Barten and Krystyna A. Stave[1]

ABSTRACT: The protection of water quality at its source - the watershed - recognizes that minimizing land use impacts and allowing natural processes to provide *in situ* biological treatment can complement conventional engineering methods. In contrast to the enormous costs projected for drinking water filtration, the judicious application of watershed management principles and practices is a way to balance the needs of people with the capacity of the natural resource base over time. This paper describes the development and initial application of a geographic information system (GIS) to a portion of New York City's 2,000 square mile water supply system, the Esopus Creek watershed in the Catskill Mountains. Primary GIS layers depict topography, soils, vegetative cover, and land use. Secondary and derivative layers help to identify the primary streamflow and sediment source areas within the watershed. Although this method is a static representation of the landscape, it can serve as a guide to field inspections and related research to prioritize land for a conservation easement or protection program or to locate unstable areas in urgent need of restoration. Subsequent research includes the influence of contributing area, flow path, and soil properties on the travel time of subsurface flow.

KEY TERMS: Water quality, GIS, streamflow source areas, soil erosion, New York City water supply

INTRODUCTION

The direct connection between undisturbed forests and abundant quantities of pure water has been recognized for centuries. Decades of scientific research have greatly enhanced our understanding of the complex and interconnected workings of forested watersheds (Likens *et al.*, 1977; Swank and Crossley, 1988). More recently, environmental monitoring and modeling have provided the means to extend some of the findings of detailed watershed experiments to the regional scale. In addition to an advanced understanding of undisturbed ecosystems, the capability to characterize the effects of land use changes on the quantity and quality of water flow from catchments has developed rapidly. However, until a generalized hydrological model is developed and rigorously verified, interim solutions are needed to address pressing management needs.

Accurate predictions of water yield and water quality degradation depend upon our ability to quantify the spatial variation and complex interaction of many components over large areas and extended time periods. These watershed characteristics include: the hydrogeologic setting, terrain features, soil physical and hydraulic properties, current and historical land use patterns, and vegetative cover. Regional climatic patterns also have a direct effect upon watershed structure and function. As the rule rather than the exception, spatial and temporal variation is evidenced by field observations of differential contribution to water and sediment yield. In contrast to urban watersheds with hydrologic regimes that are dominated by overland flow from impervious surfaces, shallow subsurface flow is the principal mechanism of streamflow generation in forested watersheds. In the relatively limited area where overland flow occurs near stream channels, it is usually caused by saturation from below.

[1] Associate Professor of Water Resources and Doctoral Candidate, respectively. Yale University, School of Forestry and Environmental Studies, 205 Prospect St., Sage Hall, New Haven, CT 06511

The spatial variation of the streamflow source area reflects the portions of a watershed where shallow subsurface flow and saturation overland flow intersect the channel network (Dunne and Leopold, 1978). It is directly influenced by the morphometry of the stream system and soil attributes such as: infiltration capacity, hydraulic conductivity, porosity, and thickness in the riparian zone (Brooks *et al.*, 1991; Pearce *et al.* 1986). Maintaining or improving the quality and availability of water, for critical uses such as municipal supply, largely depends upon appropriate land use management within these critical source areas. Differences in residence time and the pathway of flow through, or in some cases over, the soil will largely account for the differential impact of similar land uses.

While basic biophysical information, professional judgement, and common sense can often guide assessments of individual sites and projects, it is difficult to develop a comprehensive and reasonably objective view of land use - water quality interactions for large, heterogeneous watersheds. Until recently, the unwieldy task of systematically merging and analyzing heterogeneous data at the watershed scale has usually led to relatively subjective land capability classification schemes or site specific environmental quality reviews. These approaches tend to average disparate characteristics over large and diverse areas or neglect downstream impacts in order to complete the task at hand. The 2,000 square mile watershed area of the New York City water supply system presents many obstacles to comprehensive and objective analyses. The sheer size and diversity of this ecosystem underscores the need for rapid assessment with a generalized analytical method and readily available data. Advances in computer hardware and software (e.g., Eastman, 1992; Tomlin, 1990) have greatly improved spatial analysis and cartographic modeling capabilities, and consequently, the ability to perform environmental impact assessments. A Geographic Information System (GIS) allows researchers and managers to account for the heterogeneity of watershed characteristics when designing water quality protection strategies.

The protection of water quality at its source recognizes that minimizing land use impacts and allowing natural processes to provide *in situ* biological treatment can complement conventional engineering methods. In contrast to the enormous projected costs ($5 to $8 billion) for water filtration in the New York City system, the conservative application of watershed management principles and practices holds considerable promise. This paper briefly summarizes the development and application of a GIS to characterize streamflow and sediment source areas in the Esopus Creek watershed - a part of New York City's water supply system (Barten *et al.*, 1994) as one part of a comprehensive watershed management program.

OBJECTIVES

The principal objectives of this study are summarized below.

1. Develop a GIS (topography, soil type, vegetative cover/land use, secondary and derivative layers) for the Esopus Creek watershed as the foundation for analyses of watershed structure and function.

2. Use the GIS to produce a spatially-referenced estimate of potential rates of subsurface flow and soil erosion to develop a first approximation of source areas for streamflow and sediment.

STUDY SITE DESCRIPTION

The study area is located in the Catskill System of the New York City water supply; Major (1992) provides a comprehensive description of the entire system. The Esopus Creek is the principal tributary to the Ashokan Reservoir (Figure 1). It supplies, along with an inter-basin transfer from the Schoharie Reservoir, about 40 percent of New York City's daily water use (1,500 MGD). The Esopus Creek watershed comprises an area of 49,494 hectares (122,415 acres or 191.3 square miles) in the northeastern portion of the Catskill Mountains. The Catskills are located near the eastern edge of the Allegheny Plateau physiographic region, bounded by the Hudson River valley to the east and the Mohawk River and the old Erie Canal to the north (Isachsen *et al.*, 1991). Elevations range from 193 meters (633 feet) above sea level at the watershed outlet to 1,281 meters (4,204 feet) at the top of Slide Mountain. Average annual precipitation is approximately 1,200 mm (47 inches), half of which falls during the April to October growing season. The average air temperature is -4 °C (24 °F) in January and 22 °C (71 °F) in July (USDA SCS 1979).

The Esopus Creek watershed contains 77 soil mapping units (USDA SCS 1979; USDA SCS 1993). These soil mapping units are derived from parent material that includes the folded and tilted shale, siltstone, and slate bedrock underlying the region, and glacial till deposited during the last period of glaciation. The landscape is characterized by knolls, low hills, and northeast-southwest ridges. Higher elevations have shallow, often excessively drained soils formed in glacial till. Rock outcrops are common along ridges. Soils in upland areas are rocky, containing large boulders and thin, flat fragments of sandstone, shale or slate. Soils on lower slopes and in the valleys, are deeper and less well drained, with a smaller proportion of rock fragments. On upper slopes, and along ridges and high plateaus, soils are relatively shallow and uniform in permeability. Soils are deeper in saddles, at lower elevations, and in stream valleys. These deeper soils tend to have two distinct layers with different permeabilities.

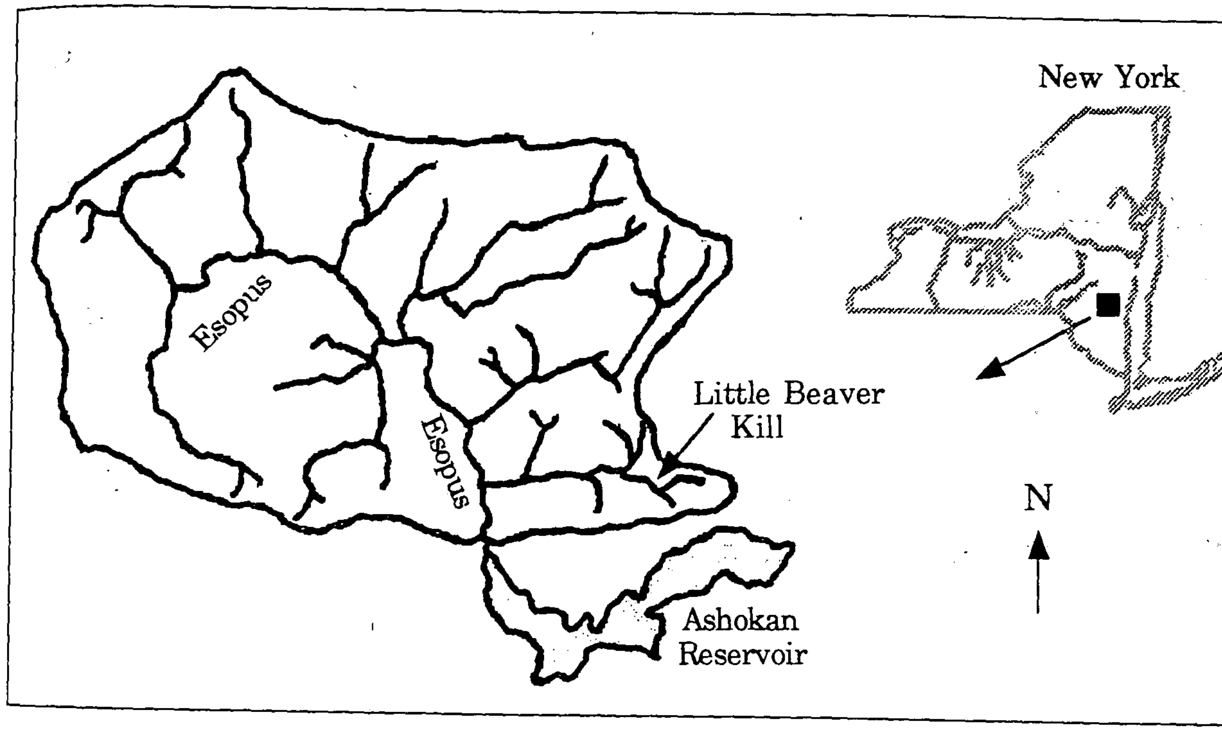

Figure 1. Location map for the Esopus Creek watershed, Catskill Mountains, New York

The Esopus Creek watershed has about 4700 permanent residents (U.S. Bureau of Census, 1990). Although this average population density of 25 persons per square mile is low by northeastern standards, the terrain features and road system concentrate most of the development and habitation in the valleys. At present, there is no large-scale agricultural land use. The political jurisdictions in the Esopus Creek watershed include three counties, eight townships, and several small villages.

The majority of uplands support mixed species stands of deciduous trees. Approximately 25 percent of the deciduous stands, mostly on the high elevation, south aspects, have a dense understory of mountain laurel (*Kalmia latifolia*). Conifers, including Eastern white pine (*Pinus strobus* L.), red pine (*Pinus resinosa* Ait.), and Eastern hemlock (*Tsuga canadensis* (L.) Carr.), are in the valley bottoms, along stream channels at higher elevations, and between ridges on the north aspects. The summits of three highest peaks (above 1100 m [3600 ft] on Slide, Wittenberg and Cornell Mountains) have stands of balsam fir (*Abies balsamifera*) and red spruce (*Picea rubens*).

METHODS

Identifying streamflow and sediment source areas for a site involves several steps: (1) delineating the watershed boundaries, (2) compiling and collecting spatially-referenced biophysical data, (3) converting the data to a uniform map scale, (4) entering the data into the GIS, (5) transforming the data into the appropriate dimensions for analysis, and finally, (6) combining the data layers to create new maps of streamflow and sediment source areas. Readily available data from the U.S. Geological Survey (USGS), USDA Soil Conservation Service, and the EROS Data Center (USGS-NASA) formed the foundation of the analyses. We divided the Esopus watershed into seven units, including: the five major tributaries, a cluster of adjacent smaller tributaries, and the main stream corridor. One of the principal tributaries, the Little Beaver Kill (4,339 ha), is used as an example in this paper. We created a base map for each unit by tracing its watershed boundary, any perennial streams, lakes and ponds, major roads, and town boundaries from USGS 7.5 minute (1:24,000) quadrangles.

Our GIS (in Idrisi version 4.0, Eastman 1992) analysis relies upon three primary layers of spatial information in raster (grid cell) format. The primary layers, with 30 meter grid cells (0.09 hectares or 0.22 acres), are topography (USGS digital elevation model [DEM]), soil type (Figure 2a; USDA SCS Soil Surveys), and vegetative cover/land use (Figure 2b; derived from enlargements of NHAP color infrared, high altitude aerial photographs). The vegetative cover/land use layer does not represent property boundaries or political jurisdictions, but categorizes vegetative cover types and land uses in order to estimate their influence on soil erosion.

The primary GIS layers and base map were used to develop secondary layers by linking specific attributes to each soil or vegetation type. We created secondary layers to depict the soil physical (erodibility) and hydraulic properties (thickness, porosity, permeability) that influence the movement and storage of water, and land cover classifications that affect erosion rates. We used a standard GIS module to create the slope layer from the elevation data (Figure 3). The derivative, or calculated, layers of spatial information were generated in the sequence shown in Table 1. The derivative layers show the relative contributions of different watershed areas to streamflow generation and soil erosion.

Table 1. GIS layers for the Esopus Creek watershed database

Primary Layers	Secondary Layers	Derivative Layers
Topography	Slope gradient	
	S factor	
	L factor	
Soil	Permeability	Flux
	Porosity	Flow
	Thickness	Total storage
	K factor	Soil erosion
Vegetation/ Land Use	VM factor	

Each of the soils was represented by either a one-layer or a two-layer system, depending upon the vertical variation in permeability. Where a clear difference (e.g., greater than twofold) in permeabilities existed between layers, we classified the soil as a two-layered system. Where permeability was relatively uniform, we classified the soil as a one-layer system. Porosity was calculated from the bulk density data for each soil layer; an adjusted value for porosity was calculated with the percent coarse fraction estimated in the field by the SCS soil surveyors. Conventional spreadsheet software was used to compile and manage this extensive database. In the case of soil complexes, which are composed of several different soil mapping units, properties were calculated as an area-weighted average of the various soil types.

Soil erosion rates are generally low when an area is protected by forest vegetation. Leaves and stems intercept precipitation, dissipating its kinetic energy, while the leaf litter protects the soil surface from raindrop splash. High infiltration rates greatly limit the incidence of overland flow. However, differences in leaf area, understory vegetation, and the length of time without leaves accounts for

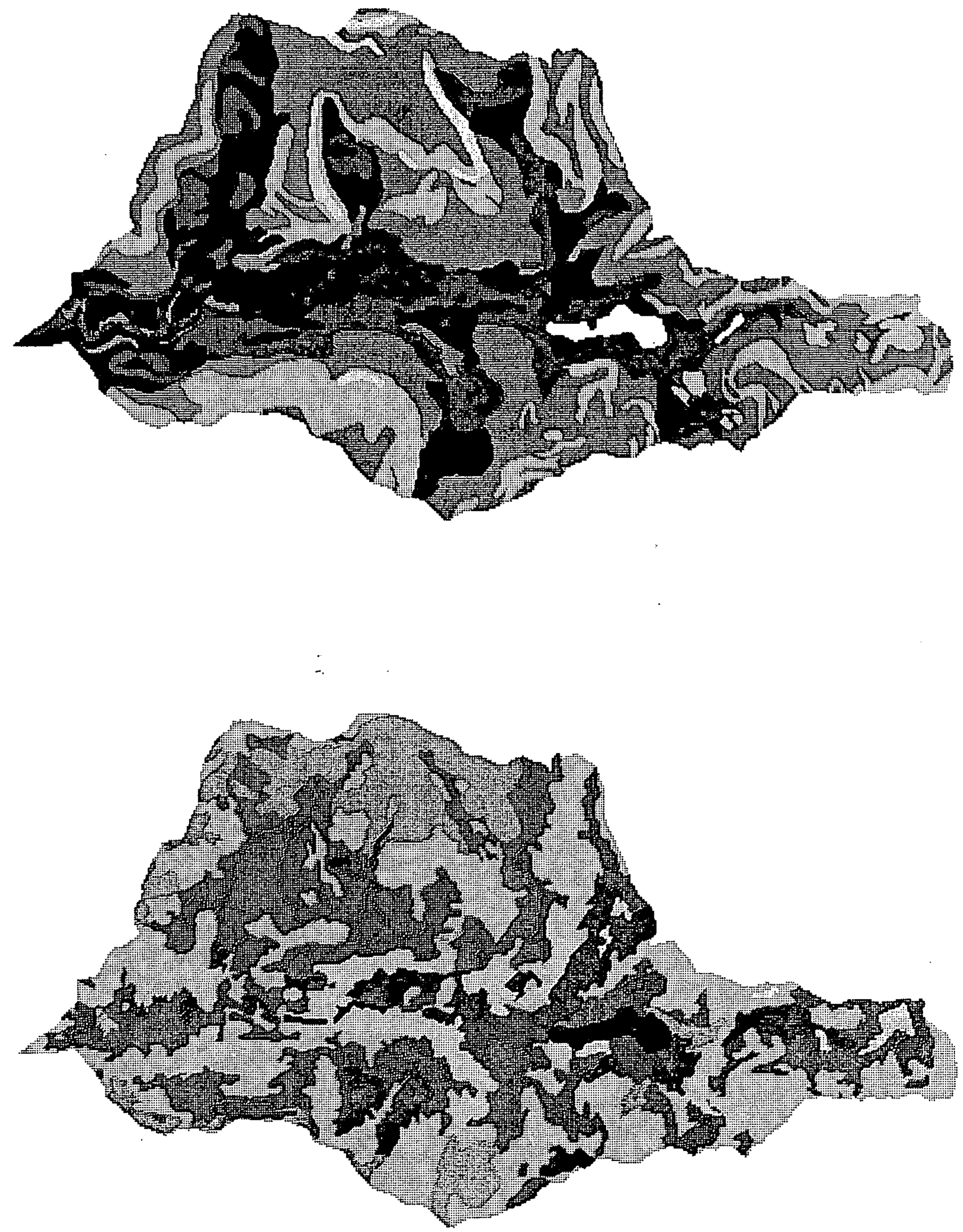

Figure 2. (a) Soil types in the Little Beaver Kill watershed. The light gray tones represent shallow, stony soil types in the uplands. The dark gray tones represent deeper, but coarse textured, alluvial deposits in the valleys. (b) vegetative cover and land use; fields and impervious areas are the lightest gray tones, three types of deciduous forest occupy the majority of the watershed, the dark gray tones represent coniferous forests.

the variation in soil erosion rates and sediment yield between otherwise similar forest stands. Therefore, we identified five forest categories, they are: (1) high density coniferous, (2) medium density coniferous, (3) mixed forest, (4) deciduous with mountain laurel understory, and (5) deciduous without mountain laurel understory. The other vegetative cover/land use categories include: fields (including lawns around residences), water features (ponds, lakes, wetlands), impervious areas (paved and rock outcrops) (Figure 2b).

The *potential* flux of water (q_S) through saturated soil is described by Darcy's Law (Hillel, 1980). The ability of each area of the watershed (each grid cell) to transmit water is governed by slope gradient and soil permeability. The potential transmission rate (flux) under saturated conditions was calculated for each grid cell using the following computational form of Darcy's Law.

$$q_{Si} = K_{Si} * [\% \text{ slope}/100] \qquad (1)$$

where:

q_{Si}	= flux [(m³/day)/m²]
K_{Si}	= permeability [(m³/day)/m²]
[% slope/100]	= estimate of hydraulic gradient (dimensionless)
i	= soil layer 1, 2

Annual soil erosion was estimated for each 0.09 hectare (0.22 acre) grid cell within the watershed with the Modified Universal Soil Loss Equation (MSLE; Wischmeier, 1965; US EPA 1980). In its current form, the GIS (Eastman 1990) does not provide for the simulation of sediment transport between grid cells. The two most influential terms with respect to the site conditions in the Esopus Creek watershed are the slope steepness (S) and vegetation management (VM) factors. The VM factor is the ratio of soil loss from land managed under specified conditions to the corresponding loss from bare soil (control) plot. Hence, it ranges from 0 to 1 as site conditions range from well-protected (e.g., forest land) to no protection (e.g., a construction site). The VM factors applied in this study were derived from US EPA estimates (US EPA 1980). In some cases, the VM factors were modified with reference to the USDA Soil Conservation Service (1983) National Engineering Handbook. VM factors range from 0.0006 for high density conifer stands to 0.013 for residential land.

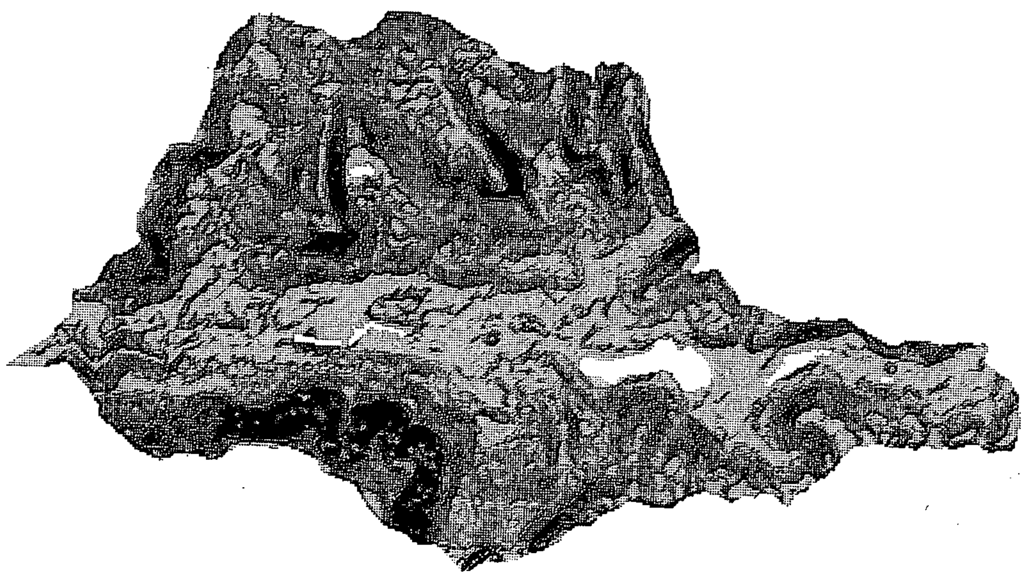

Figure 3. Slope gradient represented in 16 classes; white equals ponds and wetlands, light gray to black represents 5 percent increment classes ranging from less than 1 to 70 percent calculated from USGS digital elevation model (DEM).

RESULTS AND DISCUSSION

Predicted subsurface flux for the upper soil layer in the Little Beaver Kill subwatershed is shown in figure 4a. The results shown for the Little Beaver Kill are representative of the other six analysis units. Spatial variation in subsurface flux leads directly to differences in soil water content; ranging from at or near saturation (dark gray tones) in the primary source areas of the stream to very dry areas (light gray tones) along ridges and steeper slopes, or in deep, highly permeable, lowland deposits of sand and gravel. In essence, this is a quantitative depiction of soil drainage class.

While porosity limits the total amount of water that a given volume of mineral soil can store, it is most often inversely related to soil permeability. The diameter distribution, shape, and arrangement of the pore space has a greater influence on permeability than the total porosity (Hanks and Ashcroft 1980; Hillel 1980). Therefore, the silts and clays, although capable of greater water storage, usually transmit water to streams at a much slower rate. In contrast, sand and gravel deposits can readily transmit large volumes of water through interconnected, large diameter pores. Consequently, at any given time, the slowly permeable, poorly-drained clay soils will be wetter than the highly permeable, well-drained sandy soils. As a result, the relative contributions of different soil types along a drainage catena vary in a systematic manner.

The wet soils in close proximity to the stream channel contribute continuously to streamflow (both baseflow and stormflow). Droughty soils near the watershed divide only rarely contribute to streamflow (Brooks *et al.*, 1991; Pearce *et al.* 1986). The notable exceptions are very large rainfall or snowmelt events, on saturated or frozen soil, that overwhelm the storage capacity of the watershed. In most cases, however, the majority of the precipitation that falls on droughty soils is returned to the atmosphere via evapotranspiration as the water moves slowly downslope through unsaturated soils. During the dormant season, when evaporative demand is low, the lateral flow from upland areas may augment the soil water storage in the riparian zone.

In its current form, the GIS analysis does not account for differences in the contributing area upslope from each grid cell, yet it does depict the relative drainage rate of each portion of the watershed. A forthcoming paper will describe the estimation the flow path and travel time of subsurface flow for this site (Barten *et al.*, in prep.).

It is well known that soil erosion does not equal sediment delivery. In general, the sediment delivery ratio (total sediment load/total soil erosion) is inversely proportional to watershed area (Roehl, 1962). As the size and diversity of landscape features increases, the opportunity for eroded soil to be re-deposited before reaching the stream channel network, also increases. In the Esopus Creek watershed, the relatively high rates of soil erosion predicted on steep slopes with thin, weakly aggregated soil are often separated from the adjacent stream by a zone of high permeability soil with a low slope gradient. Overland flow encounters a hydraulically rough surface (riparian zone vegetation, leaf litter, hummock and hollow microtopography) or simply infiltrates back into the soil to join the stream as shallow subsurface flow. In either case, most of the sediment load is deposited in the riparian zone.

The results of soil erosion calculations were summarized for each analysis unit in four classes. Figure 4b shows sample results for the Little Beaver Kill subwatershed. The proportion of the watershed with predicted annual erosion rates less than 0.1 tons/acre corresponds to the natural conditions of soil formation and weathering. The second category (0.1 to 1.0 tons/acre) of annual soil erosion could produce detectable sediment concentration (if it reaches the stream) during large stormflow events. The third category (1.0 to 5.0 tons/acre) corresponds to rates of accelerated erosion that are usually linked to human activities. Erosion rates of this magnitude can be expected to produce visible sediment concentrations during stormflow events. Annual soil erosion rates in excess of 5.0 tons/acre are cause for concern and prompt attention in watershed management programs. The USDA Soil Conservation Service considers this rate to exceed the regenerative capacity of most soils. The loss of fine particles (clay and silt) and organic matter leads to losses in fertility. Declining fertility reduces the biomass and vigor of vegetation, further reducing the site's resistance to erosion. Proactive management is usually required to stabilize the site and reverse this destructive sequence.

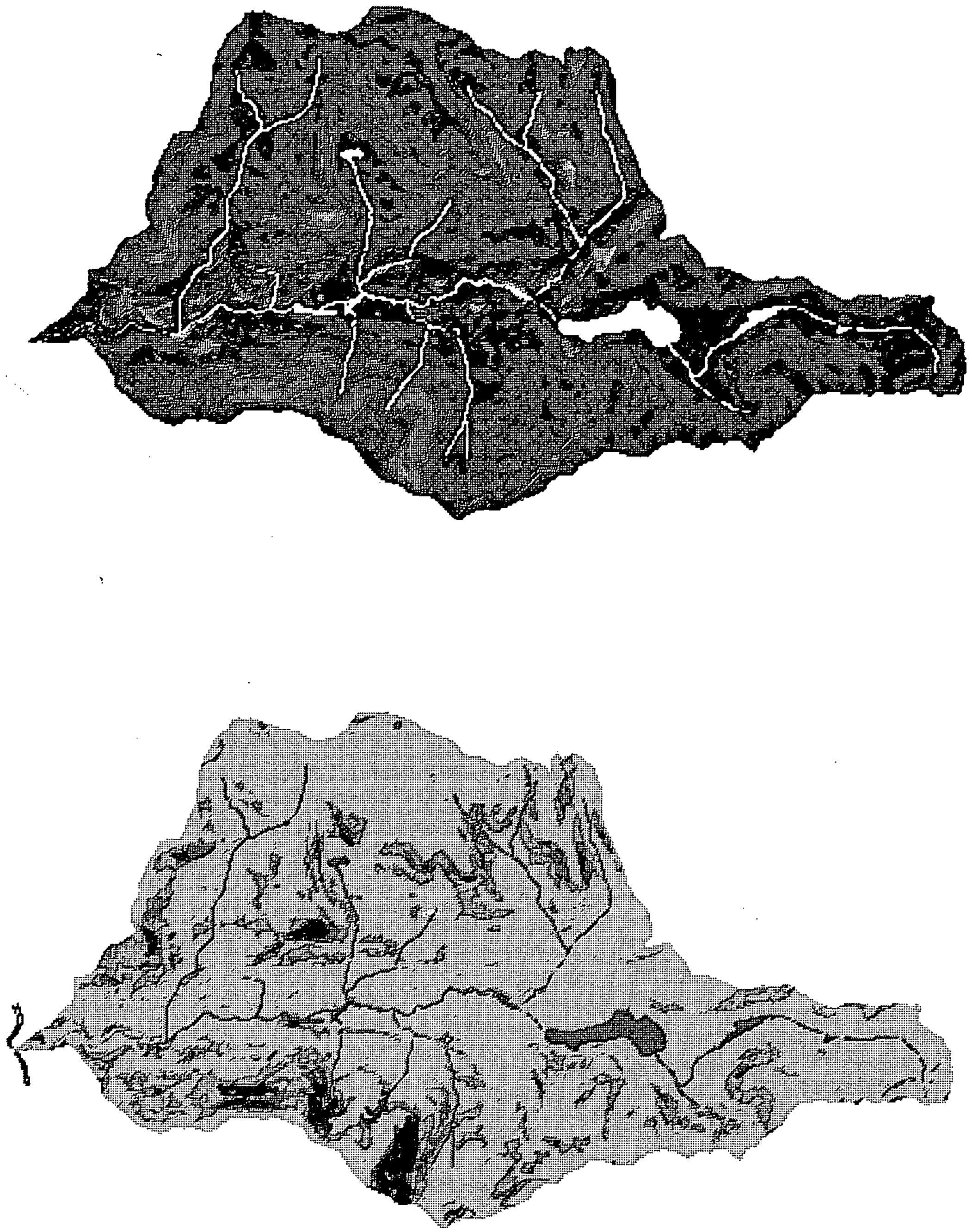

Figure 4. (a) Estimated potential subsurface flux in the upper soil layer of the Little Beaver Kill watershed. White areas are streams, wetlands, and ponds. The gray scale ranges from 0 - 0.1 (black) to 0.8 - 0.9 (lightest gray) ([m^3/day]/m^2) in equal 0.1 increments. (b) Estimated annual soil erosion (tons/acre); Seven categories (0.5 ton/acre increment) show soil erosion rates from 0 - 0.5 (lightest gray) to 3.0 - 3.5 (black). The Little Beaver Kill is a principal tributary to the Esopus Creek in the Catskill Section of the New York City Water Supply.

CONCLUSIONS

The derivative layers produced by our analyses of the Esopus Creek watershed can be used to guide more detailed field research and resource management decisions. For example, the standard watershed management practice of protecting a fixed width buffer strip along all perennial streams could be supplemented with the protection of additional areas. The preliminary identification of land for acquisition or the purchase of conservation easements also could be based upon figures 4a and 4b.

The black areas (poor drainage leading to frequent generation of streamflow) that intersect the perennial streams and water features (shown in white) in figure 4a should be considered for protection. Since the results presented in this paper do not include the quantification of flow paths and contributing areas, the priority assigned to particular sites should consider the relative position within each watershed analysis unit. Simply put, the black areas that intersect the stream system near the center of the watershed are likely to be more important than the sites near the watershed boundary.

Fortunately, the existing land uses and vegetative cover provide good protection from soil erosion throughout most of the Esopus Creek watershed. If predicted soil erosion is used as a proxy for nonpoint source pollution (dissolved, suspended, and adsorbed to sediment) generated by land use, then the identification of source areas is important for protection and restoration. Again, dark areas intersecting the stream network in figure 4b are likely candidates for active management and protection. This identification of likely nonpoint sources should be coupled with conventional compliance monitoring for domestic wastewater (septic systems) and stormwater (road drainage). Areas with relatively high erosion rates cannot be equated with high sediment transport to the stream system. The condition of surrounding areas has a significant influence on the generation and transport of nonpoint source pollution.

In all cases, the portions of the watershed identified for protection with the GIS-based analyses should be field checked. Although there are a range of possible refinements, the holistic view of the watershed offered by the GIS can help to design and implement effective management practices.

ACKNOWLEDGEMENTS

This research was supported by the New York City Department of Environmental Protection Stream Corridor Protection Program, the Yale School of Forestry and Environmental Studies, and the U.S. Man and the Biosphere Program. Anthony J. Cahill, Sean Murphy, and J. Wolfe Tone worked on the development of the GIS database.

REFERENCES

Barten, P.K., T.W. Ostrom, A.J. Cahill, and M.V. Warren., (in preparation) A GIS-based hydrological model to estimate the pathway and rate of subsurface flow in forested watersheds. for Water Resources Bulletin.

Barten, P.K., K.A. Stave, A.T. Cahill, S. Murphy, and J.W. Tone., 1994. Characterization of streamflow and sediment source areas in the Esopus Creek watershed, Ulster, Greene, and Delaware Counties, New York. Final Project Report, NYC DEP, 166 pp.

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, and J.L. Thames., 1991., Hydrology and the Management of Watersheds., Iowa State University Press, Ames, Iowa, 392 pp.

Dunne, T. and L.B. Leopold, 1978. Water in Environmental Planning. W.H. Freeman Company, San Francisco, CA, 818 pp.

Eastman, J.R., 1992. IDRISI: A grid-based geographic analysis system. (Version 4.0) Clark University, Graduate School of Geography, Worcester, MA, 256 pp.

Hanks, R.J., and G.L. Ashcroft., 1980. Applied Soil Physics. Springer-Verlag, NY, 159 pp.

Hillel, D., 1980. Fundamentals of Soil Physics. Academic Press, NY, 413 pp.

Isachsen, Y.W., E. Landing, J.M. Lauber, L.V. Rickard, and W.B. Rogers (Editors), 1991. Geology of New York: A simplified account. New York State Museum/Geology Survey, NY State Education Department, Albany, 284 pp.

Likens, G.E., F.H. Bormann, R.S. Pierce, J.S. Eaton, and N.M. Johnson., 1977. Biogeochemistry of a Forested Ecosystem. Springer-Verlag, NY, 146 pp.

Major, D.C., 1992. Urban water supply and global environmental change: The water supply system of New York City. In: Proc. 28th Annual AWRA Conference and Symposium: Managing water resources during global change, R. Hermann (Editor): 377-385.

Pearce, A.J., M.K. Stewart, and M.G. Sklash., 1986. Storm runoff generation in humid catchments 1: Where does the water come from? Water Resources Research 22(8):1263-1272.

Roehl, J.W. 1962. Sediment source areas, delivery ratios and influencing morphological factors. International Association of Hydrological Sciences Publication no. 59.

Swank, W.T., and D.A. Crossley, Jr., (Editors) 1988. Forest Hydrology and Biology at Coweeta. Springer-Verlag, NY, 469 pp.

Tomlin, C.D., 1990. Geographic Information Systems and Cartographic Modeling. Prentice Hall Publishing Company, Englewood Cliffs, NJ, 249 pp.

US Bureau of the Census. 1990. Survey of Population and Housing.

USDA Soil Conservation Service (USDA SCS). 1993. Soil Survey of Greene County, New York.

USDA Soil Conservation Service (USDA SCS), 1983. National Engineering Handbook., Chapter 3: Erosion, Section 3: Sedimentation.

USDA Soil Conservation Service (USDA SCS), 1979. Soil Survey of Ulster County, New York.

US Environmental Protection Agency (US EPA), 1980. An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources (A Procedural Handbook). EPA-600/8-80-012.

Wischmeier, W.H., 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. USDA ARS, Handbook 282.